

Depth-averaged Simulation of Flows in Asymmetric Compound Channels with Smooth and Rough Narrow Floodplains

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Abstract

Depth-averaged hydrodynamic models are predominantly used in numerical simulations of compound channel flows. One of the most popular methods for the depth-averaged simulation is Shiono and Knight method (SKM). This method accounts for the effects of bed friction, lateral turbulence and secondary flows, via three key parameters f , λ & Γ respectively. The conventional expressions that are developed by Abril and Knight (2004) to calibrate these parameters are generally based on experiments in compound channels with wide floodplains. In this study, the application of SKM to an asymmetric compound channel with a narrow floodplain is examined in terms of the calibration requirements. Two sets of experiments that have smooth and rough floodplain and different flow depths are conducted and then simulated by SKM. In smooth floodplain cases, the results reveal that SKM model with the conventional calibration expressions of f , λ and Γ is reasonably capable of predicting the distributions of depth-averaged velocity and boundary shear stress in the main channel. However, in the floodplain region, the expressions recommended for calibrating Γ need to be modified to improve the predicted results in that region. In cases of the rough floodplain, the results indicate that the lateral shearing is dominant over the secondary flow, so only the values λ in the main channel need to be changed from its conventional values to improve the predictions.

Keywords: Asymmetric compound channel, SKM, Depth-averaged velocity, boundary shear stress, Narrow floodplains.

1 Introduction

Most rivers consist of a relatively deep channel with adjacent shallow floodplains so that the flow section takes a two-stage geometrical shape usually called a compound channel. The differences in water depth and bottom friction of the main channel and the floodplain regions cause the velocity in the floodplain to be lower than that in the main channel, generating a transverse gradient in streamwise velocity. This transverse gradient in the velocity and that in the bottom level of the channel create a mixing zone and cause exchange of mass and momentum. As consequence of that, the prediction of the key flow variables (such as the velocity and shear stress) in such a compound channel requires adequate modelling of flow features such as the

momentum exchange and secondary flow cells that occurs at the main channel/floodplain interface (Shiono and Knight 1991; van Prooijen et al. 2005).

Many studies have concerned with the prediction of the depth-averaged velocity and boundary shear stress in compound channels, e.g. Ervine & Ellis (1987); Shiono and Knight (1988, 1991); Wark et al. (1990); Lambert and Sellin (1996); Ervine et al. (2000); Spooner & Shiono (2003); Van Prooijen et al. (2005) and Yang et al. (2012). Based on these studies, a number of two-dimensional approaches for modelling the depth-averaged velocity and the boundary shear stress distributions have been developed. However, the methodology proposed by Shiono and Knight (1991), which is based on Reynolds averaged Navier–Stokes (RANS) equation, is the most popular method and is widely used for modelling different cases associated with the compound channel flows. Therefore, this paper concentrates only on the application of the SKM methodology to asymmetric compound channels that are considered here.

The Shiono and Knight method (SKM) provides an analytical solution for the lateral distributions of depth-averaged velocity and bed shear stress, accounting for the effects of the bed friction, lateral eddy viscosity, and secondary flow cells by means of three hydraulic parameters (f for friction, λ for eddy viscosity, and Γ for secondary flow). Based on the SKM method, many investigations have been undertaken into flow in straight and meandering compound channels. For example, the SKM method has been applied to straight prismatic channels by Shiono & Knight (1991); Abril and Knight (2004); Liao and Knight (2007); Tang & Knight (2008a); Knight & Tang (2008); Seckin et al. (2009); and Devi & Khatua (2016). Attempts have also been undertaken to use the SKM in modelling meandering channels (Liu et al. 2014) and non-prismatic channels (Rezaei & Knight 2009 and Chlebek 2009). Knight et al. (2007) and Tang & Knight (2008b) have shown that the SKM can satisfactorily be applied to in-bank symmetrical channels (including trapezoidal and single section with a vertical wall channels). Furthermore, the SKM methodology was employed in Conveyance Estimation System (CES) software, which provides a practical methodology for predicting velocity and estimating flow capacity in rivers, McGahey et al. (2006).

Although the SKM method was frequently used for estimating the depth-averaged velocity in compound channels with varying width ratios, relative depths, relative roughness and main channel side slopes, there have been relatively few studies conducted to examine the

applicability of the method on the channels with narrow floodplains. Such a narrow floodplain channels can be existing in many cases and it would be more factual to modelling them as a compound channel than be approximating as a simple trapezoidal cross-section as shown in Figure 1.

[Figure 1 can be inserted here]

Thus, the current research presents the application of SKM to determine the depth-averaged velocity and boundary shear stress distribution in compound channels with narrow floodplains having different roughness conditions. An analysis of calibrating the key parameters (f , λ and Γ) used in the model was also performed to establish modified calibration expressions that are fit to narrow floodplain channels. To perform the analysis, two series of experiments were conducted on an asymmetric compound channel with a narrow floodplain.

2 Depth-averaged modeling using SKM method

The depth-averaged simulations of flows in the compound channels considered in the present study was carried out by using Shiono and Knight method (SKM). Therefore, it is necessary that a detailed description of the SKM method is given first.

According to this method, Navier–Stokes equation for steady and uniform flow in streamwise direction is combined with the continuity equation to give the following equation (Shiono and Knight 1991):

$$\rho \left[\frac{\partial}{\partial y} (UV) + \frac{\partial}{\partial z} (UW) \right] = \rho g S_o + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \quad (1)$$

where U , V and W are the temporal mean velocity components in x , y and z direction, x is streamwise axis that is parallel to the channel bed; y is lateral and z is normal to the bed, ρ is fluid density, g is gravitational acceleration; S_o is channel bed slope, τ_{yx} and τ_{zx} are Reynolds stresses on planes perpendicular to the y and z directions, respectively. In the depth-averaged modeling, the depth-averaged velocity, bed shear stress and depth-averaged viscosity are given by:

$$U_d = \frac{1}{H} \int_0^H U dz; \quad \tau_b = \left(\frac{f}{8} \right) \rho U_d^2; \quad \varepsilon_{yx} = \lambda U_* H \quad (2)$$

where U_d is depth-averaged velocity, H is local water depth, τ_b is local bed shear stress, U_* is shear velocity ($=\sqrt{\tau_b/\rho}$), f is friction factor and λ is defined as dimensionless eddy viscosity. The Reynolds shear stress τ_{yx} acting on lateral planes can be expressed based on the eddy viscosity theory as follows:

$$\tau_{yx} = \rho \varepsilon_{yx} \frac{\partial U_d}{\partial y} \quad (3)$$

where ε_{yx} is the depth-averaged eddy viscosity.

Shiono and Knight (1991) simplified Eq. (1) by making use of the expressions in Eqs. (2 & 3) and then integrated the equation over the total flow depth to obtain the depth-averaged form of Eq. (1):

$$\rho g H S_o - \rho \frac{f}{8} U_d^2 \left(1 + \frac{1}{S^2}\right)^{\frac{1}{2}} + \frac{\partial}{\partial y} \left[\rho \lambda H^2 \left(\frac{f}{8}\right)^{1/2} U_d \frac{\partial U_d}{\partial y} \right] = \frac{\partial}{\partial y} [H(\rho UV)_d] \quad (4)$$

Equation (4) is the basic form of Shiono and Knight method (SKM) that is widely used for depth-averaged calculations in simple and compound channel flows.

The term on the right-hand side of Eq. (4) accounts for the effect of the secondary flow on the primary flow. Shiono and Knight (1991) observed that the lateral gradient of the secondary flow term $[H(\rho UV)_d]$ decreases approximately linearly in the main channel and linearly increases on the floodplains. Therefore, they suggested that a constant value of secondary flow term, which is referred to as secondary flow parameter (Γ) can be allocated for main channel and floodplains. Thus, Eq. (4) can be rewritten as follows:

$$\rho g H S_o - \rho \frac{f}{8} U_d^2 \left(1 + \frac{1}{S^2}\right)^{\frac{1}{2}} + \frac{\partial}{\partial y} \left[\rho \lambda H^2 \left(\frac{f}{8}\right)^{1/2} U_d \frac{\partial U_d}{\partial y} \right] = \Gamma \quad (5)$$

For a rectangular compound channel such as a channel considered in this study, Eq. (5) can be solved analytically for U_d distribution over a flow region with a constant depth and the solution is given as follows (Shiono and Knight, 1991):

$$U_d = [A_1 e^{\gamma y} + A_2 e^{-\gamma y} + k]^{1/2} \quad (6)$$

where γ and k are given as follows:

$$k = \frac{8gS_oH}{f}(1 - \beta); \quad \beta = \frac{\Gamma}{\rho gHS_o}; \quad \gamma = \sqrt{\frac{2}{\lambda}} \left(\frac{f}{8}\right)^{1/4} \frac{1}{H} \quad (7)$$

A_1 and A_2 are unknown constants and need to be determined through imposing appropriate boundary conditions on the solution domain.

The accuracy of the SKM results was found to depend substantially on the three depth-averaged calibration coefficients, which includes local bed friction (the Darcy-Weisbach friction factor) f ; the dimensionless eddy viscosity λ and the transverse gradient of secondary flow term Γ . In the compound channel with wide floodplains, different methods have been suggested to calibrate each one of these three coefficients. The friction factor is often assumed to be constant in each panel and may be back calculated using ($f = 8\tau_b / U_d^2$), where the mean depth-averaged velocity U_d and shear stress τ_b are measured for each panel (Knight et al. 2007). The dimensionless eddy viscosity for the main channel (λ_{mc}) is usually taken as 0.07 for experimental channels and from 0.24 to 0.5 for natural channels (Knight and Shiono 1990; Shiono and Knight 1991; James and Wark 1992). The value of the dimensionless eddy viscosity for the floodplain (λ_{fp}) is mostly predicted by the expression proposed by Abril and Knight (2004) and given as follows:

$$\lambda_{fp} = \lambda_{mc}(1.2D_r^{1.44} - 0.2) \quad (8)$$

where D_r is the relative depth and defined as the ratio between the flow depth of the floodplain to that of the main channel. The secondary flow parameter (Γ) can be defined as a fraction of the bed shear stresses (ρgHS_o), (Abril 1997; Abril and Knight 2004 and Omran 2005). The simplification for the secondary flow term may also be made by expressing the term of V_d as a function of the U_d , (Ervine et al. 2000). The assumption is that the product of the local U_d and V_d velocities produce a profile that is similar to that of the squared depth-averaged streamwise velocity. Therefore, temporal mean velocities $[(UV)_d]$ in the secondary flow term, i.e. the right-hand side of Eq. (4), can be rewritten as the fraction of the depth-averaged velocity U_d in the form:

$$(UV)_d = KU_d^2 \quad (9)$$

where K is an empirical coefficient that relies on the geometry and boundary roughness.

However, using the expressions suggested for a compound channel with wide floodplains to calculate the SKM parameters may not give the calibrated values that are proper for a compound channel with narrow floodplains. In this research, the conventional approaches discussed above are checked whether they can also be applicable to the compound channel with narrow floodplains and improved if necessary.

3 Details of Experiments

In this study, two different sets of experiments were undertaken in an asymmetric compound channel with the floodplain being narrower than the main channel. The ratio of the floodplain width to the main channel width is 0.50. The compound channel was constructed inside a flume that has an overall length of 9 m using smooth plywood sheets. Figure 2 shows the setup of the laboratory flume used in the experiments.

[Figure 2 can be inserted here]

In both sets of the experiments, the compound channel had a total inside width (B) of 0.3 m and the main channel width (b) of 0.2 m, as shown in Figure 3. In all test cases, the bed slope of the channels was fixed at about 0.0070 m/m. The flow was adjusted to achieve uniform flow at a specified normal depth by using an adjustable tailgate at the downstream end of the flume. In a laboratory flume, the ability to establish and recognize uniform flow may be difficult due to the limited length of the flume. However, the best approximation for uniform conditions is when the average water surface level lies at the correct distance above the bed level and both the water and bed levels have the same slope. In the present work, this approximate approach was adopted to establish the uniform condition and determine the normal depth by measuring several profiles of M1 backwater and M2 drawdown curves. The tailgate setting which gave a mean water level slope equal to the flume bed slope was interpolated from two asymptotic M1 and M2 profiles. Experimental conditions for both sets of experiments are listed in Table 1.

[Figure 3 can be inserted here]

In the first set of experiments that includes the cases CS1, CS2, CS3 and CS4, both the main channel and the floodplain had smooth boundaries and the height of the floodplain (h) was 60 mm. The total flow depth was changed from 80 mm to 120 mm to cover a range of relative depth $Dr [= (H-h)/H]$ from 0.25 to 0.50. In these smooth floodplain cases, the Manning coefficients (n)

in the main channel and floodplain were estimated as about 0.009 by applying the Manning equation on normal depth measurements for uniform flows. In most river flow cases, Manning's n has less variation with discharge (Ladson et al. 2013). Therefore, the value of n was assumed to be constant for all discharges considered here.

On the other hand, the cases considered in the second set (i.e. CR1, CR2, CR02 and CR3) had a rough bed on the bottom of the floodplain while the main channel was kept smooth. The height of the floodplain (h) was 75 mm. A single layer of gravel particles with mean size of approximately 6.0 mm was glued over the bed of the floodplain to create a rough surface. For a bed made up of a single layer of uniform grains (sand or gravel), the equivalent roughness (K_s) is conventionally estimated to be on the order of the size of the grains that make up this layer (López & Barragán, 2008). Due to the non-uniformity of grain shape and the irregular distribution of gravels when gluing them, the roughness height K_s was estimated to be equal to the mean size of gravels (≈ 6.0 mm) in the present work. For the smooth main channel, K_s was calculated based on the Manning's n using [the relationship proposed by Ackers \(1991\) and given by Eq. \(22\)](#).

[Table 1 can be inserted here]

For measuring the depth-averaged velocity, a Pitot tube with a diameter of 3.2 mm and with 4 holes (ϕ 0.75 mm) was used in all test cases. The Pitot tube was connected to the low-range digital pressure transducer (Comark C9551/SIL, 0 to ± 140 mbar), to measure the pressure difference (Δp) between the static and dynamic pressures. Δp obtained from the output of the transducer was then used to calculate the velocity by applying Bernoulli's concept. Fifteen vertical velocity profiles spaced laterally 20 mm were measured to obtain the depth-averaged velocity distribution over the entire cross section. In each vertical profile in the floodplain, depth-averaged velocity was established from point velocity measurements at an elevation of 0.4 times the flow depth. In the main channel, eight-point measurements equally spaced along each vertical profile were taken to obtain the depth-averaged velocity. The resulting measured velocity distributions were integrated over the cross section to produce discharges that should be within $\pm 4\%$ of the discharges measured by the calibrated electromagnetic flow meter. If the difference between the integrated and measured discharges was higher than 4%, the experiments were repeated.

In the present research, the boundary shear stress was determined by using Preston tube, which is really a pitot tube with outer diameter of $d = 3.2$ mm. Boundary shear measurements along the perimeter of main channel and flood plain were taken with around 2 cm intervals. Two methods of calibration were used in measuring the boundary shear stress. For smooth boundaries, the calibration curve suggested by Patel (1965) was used. Based on Patel calibration method, which has been used for smooth boundaries, the following relationship is given to convert the pressure readings recorded by Pitot (or Preston) tube to boundary shear stresses:

$$y_* = 0.50x_* + 0.037, \quad \text{for } 0 \leq x_* \leq 2.90 \quad (10a)$$

$$y_* = -0.0060x_*^3 + 0.1437x_*^2 - 0.1381x_* + 0.8287, \quad \text{for } 2.90 \leq x_* \leq 5.60 \quad (10b)$$

$$x_* = y_* + 2 \log_{10}(1.95y_* + 4.02), \quad \text{for } 5.60 \leq x_* \leq 7.60 \quad (10c)$$

where, the two non-dimensional parameters x_* and y_* are defined as follows:

$$x_* = \log_{10} \left(\frac{\Delta P d^2}{4 \rho v^2} \right) \quad \text{and} \quad y_* = \log_{10} \left(\frac{\tau_b d^2}{4 \rho v^2} \right) \quad (11)$$

in which, d is the outer diameter of the tube, ρ is the density of the flow, v is the kinematic viscosity of the fluid.

For rough boundaries, the simple calibration equation developed by Wu & Rajaratnam (2000) was used. For a given roughness and Pitot (or Preston) tube, Wu & Rajaratnam (2000) proposed a simple calibration expression by which the shear velocity (u_*), which equal to $(\sqrt{\tau_b/\rho})$, can be calculated:

$$R_o = AR_s + aR_s + b \quad (12)$$

where R_o , R_s and A are given as follows:

$$A = 5.75 \log_{10}(z_o/K_s), \quad R_o = u_o K_s / v \quad \text{and} \quad R_s = u_* K_s / v \quad (13)$$

in which u_o is the velocity at the centre of the tube, K_s is the equivalent roughness height, z_o is the distance from the centre of the tube to the datum of the rough bed. a and b are constants which their values are found to be dependent on the values of R_s . For $R_s > 70$, as in the test cases considered in the present study, the coefficients a and b have the values of 8.5 and 0.0, (Wu & Rajaratnam, 2000).

The total shear force per unit length normal to flow cross section was calculated by integrating the shear stress measurements over the entire perimeter. The integrated total shear then compared with the theoretical shear force based on the energy gradient approach ($\rho g A S_o$). The error values obtained from two methods were found within $\pm 2.5\%$ for smooth boundaries and $\pm 5\%$ for rough boundaries.

4 Applying SKM model to the case study

4.1 Number of panels and Boundary conditions

To apply the analytical depth-averaged model based on SKM method, the channel is first divided into a sufficient number of panels and then the appropriate boundary conditions are imposed on the panels. For all test cases considered here, the asymmetric rectangular compound channels were divided into only two panels, one for the main channel and the other for the floodplain region. Because all channels simulated in this work have a regular and uncomplicated cross section, the simulations were restricted to a small number of panels. Furthermore, choosing the minimum number of panels with a reasonable useful output are typically acceptable for practical purposes since the SKM method itself is only an approximate one. However, for modeling some particular flow cases where greater precision is required, more number of panels (4 or more) may be necessary, (Knight et al. 2009).

To determine the integration constants ($A1$, $A2$) in Eq. (6), the boundary conditions need to be applied between the panels and at the channel edges. In general, there are different types of boundary conditions can be applied in the applications of SKM model. These may include:

(1) the no-slip condition at the remote edges of the channel (Figure 3),

$$(U_d)_{y=0}^i = (U_d)_{y=B}^{i+1} = 0 \quad (14)$$

(2) the continuities of the velocity (U_d) and its gradient gradients ($\partial U_d / \partial y$) at the interface between the adjacent panels (Knight et al. 2004; and Liao & Knight 2007),

$$(U_d)_{y=b}^i = (U_d)_{y=b}^{i+1}; \quad \left(\frac{\partial U_d}{\partial y} \right)_{y=b}^i = \left(\frac{\partial U_d}{\partial y} \right)_{y=b}^{i+1} \quad (15)$$

(3) the continuities of HU_d and the lateral gradient of $\partial HU_d / \partial y$ at the interface between the adjacent panels (Shiono and Knight 1991),

$$(HU_d)_{y=b}^i = (HU_d)_{y=b}^{i+1} ; \quad \left(\frac{\partial HU_d}{\partial y} \right)_{y=b}^i = \left(\frac{\partial HU_d}{\partial y} \right)_{y=b}^{i+1} \quad (16)$$

However, Tang and Knight (2008b) pointed out that there are considerable difficulties in specifying boundary conditions for rectangular compound channels where the internal wall between the floodplain and the main channel is vertical. they analyzed a wide selection of data and suggested that the continuity of unit force was technically the most suitable for the cases of vertical internal walls. Based on their analysis, the following relationship for the continuity of unit force was proposed to apply at the vertical wall between the main channel and the floodplain:

$$(H\bar{\tau}_{yx})_{y=b}^i + h\tau_w = (H\bar{\tau}_{yx})_{y=b}^{i+1} \quad (17)$$

where τ_w is averaged shear stress at the internal wall. By employing the expression that relate explicitly the Reynolds stresses with mean velocity gradients, Eq. (17) can be rewritten as follows:

$$\left(\phi \frac{\partial U_d^2}{\partial y} \right)_{y=b}^i = \left(\phi \frac{\partial U_d^2}{\partial y} \right)_{y=b}^{i+1} - h\tau_w \quad (18)$$

$$\phi = \frac{1}{2} \rho \lambda H^2 \sqrt{f/8} \text{ and } \tau_w = \rho f_w (U_d^2)_{y=b}/8 \quad (19)$$

The boundary condition given by Eq. (18) has a drawback because the wall shear stress (τ_w) at the vertical wall needs to be known in prior. Therefore, the wall shear stress (τ_w) is approximated by using the friction factor in the main channel and the depth-averaged velocity at the interface as given by Eq. (19).

Tang and Knight (2008b), based on their investigation into selecting suitable boundary conditions for a channel with an internal vertical wall, confirmed that the boundary condition given in Eq. (18) is the most appropriate one. Therefore, this type of boundary condition was applied at the vertical wall between the main channel and floodplain, while the no-slip condition was imposed at the remote edges.

4.2 Calibrating the model parameters

In addition to choosing the number of panels, the appropriate choice of values for the calibration parameters (f , λ , Γ) for each panel are also essential for correct calculations. Based on the principle involved in the SKM method, the friction parameter f is usually determined for each panel through the use of the Colebrook-White equation (Shiono and Knight 1991):

$$\frac{1}{\sqrt{f}} = -2.03 \log_{10} \left[\frac{K_s}{12.27R} + \frac{3.09}{Re\sqrt{f}} \right] \quad (20)$$

Where K_s is the roughness height, Re is the Reynolds Number and R is the hydraulic radius. This equation considers the full three-dimensional flow effects throughout the depth of flow. In spite of that, the Colebrook-White equation evaluates a lateral distribution of f at each flow region based on an iterative estimation. Therefore, a simpler formulation of the Colebrook-White equation which is developed by Rameshwaran and Shiono (2007) was used here for estimating the value of f for both the main channel and the floodplain panels. This equation can be written as follows:

$$f = \left[-2.0 \log_{10} \left(\frac{3.02\nu}{\sqrt{128gH^3S_o}} + \frac{K_s}{12.3H} \right) \right]^{-2} \quad (21)$$

where ν is kinematic viscosity. If the values of K_s are not available, they can be calculated from the relationship that relates the Manning coefficients n to the surface roughness (Ackers 1991):

$$K_s = (8.25\sqrt{gn})^6 \quad (22)$$

The resistance relationship given by Eq. (21) was used by several researchers, e.g. Sun X. (2007) and Yang et al. (2012), for estimating the friction factor in rectangular compound channels and a reasonably good agreement has been noticed between the calculated and measured values for f .

The most common method of calibrating the dimensionless eddy viscosity coefficient (λ) is the method of expressing the ratio of this coefficient between the floodplain and the main channels ($\lambda_{fp}/\lambda_{mc}$) in terms of the relative depth Dr . In this method, the coefficient of the dimensionless eddy viscosity (λ_{fp}) in the floodplain is determined by estimating a value for the coefficient (λ_{mc}) in the main channel which is usually independent of the flow depth. The value of $\lambda_{mc} = 0.07$ is

often used as the initial value in the main channel, with the following general expression used for the ratio ($\lambda_{fp}/\lambda_{mc}$):

$$\frac{\lambda_{fp}}{\lambda_{mc}} = aDr^b - c \quad (23)$$

Equation (23) was proposed by Abril & Knight (2004) based experiments conducted by Knight & Abril experiments (1996) on compound channels with a wide floodplain. They suggested that the coefficients a , b and c can take values as 1.20, -1.44 and 0.20 respectively. It should be pointed out that the initial dimensionless eddy viscosity value for the main channel, λ_{mc} , was taken to be same as the depth-averaged value assumed for a wide channel ($k/6 = 0.41/6 \approx 0.07$, where k = von Karman's constant). Although the values of λ_{fp} provided by Eq. (23) were consistent with the experimental data of Knight & Abril (1996), it is not strictly applicable to experiments considered here. It is thought that the transverse variation of the dimensionless eddy viscosity (λ) may be dependent on the roughness and width of the floodplains (Fernandes et al. 2014). Therefore, further investigation may be required to check whether Eq. (23) with the coefficients values recommended by Abril & Knight (2004) can successfully be used in the simulations of various compound channels that have different floodplains in terms of width and bottom roughness, as shown elsewhere.

The calibration of the secondary flow parameter (Γ) needs to detailed measurements of three-dimensional velocities at the junction zone between the main channel and the floodplain (Shan et al. 2016). Nevertheless, as mentioned previously, the gradient of the secondary flow term is constant within a certain zone, allowing constant values of Γ to be assigned to each panel. Hence, for a given channel, the constant values of Γ can be set for the main channel and the floodplain regions. For the simulations in the present study, the conventional expression which relates the secondary flow term to the average shear stress was used to calibrate Γ . This expression can be given for the main channel and floodplain as follows:

$$\Gamma_{mc} = k_{mc}(\rho g S_o H) \quad (24)$$

$$\Gamma_{fp} = k_{fp}(\rho g S_o H) \quad (25)$$

where k defined as the secondary flow coefficient which is different in the main channel and the floodplain regions. Based on data obtained by Shiono & Knight (1991) from the Flood Channel

Facility experiments for different relative depths in a straight compound channel, Abril & Knight (2004) recommended that $k_{mc} = 0.15$ and $k_{fp} = -0.25$ can be used as calibrated values for the secondary flow coefficients. As the secondary current term Γ varies with flow depth and geometry of the cross section (Yang et al. 2012) and may depend on the bottom roughness (Fernandes et al. 2014), so it is expected that the standard values of k suggested by Abril & Knight (2004) may not be fit to the flow cases under consideration. Therefore, this issue has been further discussed in a later section of this article.

5 Analysis of results

5.1 Flow Cases with Smooth Narrow Floodplains

The analytical SKM model was first applied to the cases of the smooth narrow floodplains (i.e. cases CS1~CS4) using the conventional calibration values of friction factor (f), dimensionless eddy viscosity (λ) and secondary flow parameter (Γ). The predicted results for the depth-averaged velocity (U_d) and the bed shear stress (τ_b) are plotted in Figures 4 & 5 and referred to as SKM1 (dashed lines). For the SKM1 application, f was estimated from the modified Darcy-Weisbach equation, Eq. (21). The dimensionless eddy viscosity parameter for the main channel (λ_{mc}) was assumed to be (0.07) and that for the floodplain (λ_{fp}) was computed from Eq. (23) using its conventional form, i.e. $\lambda_{fp} = \lambda_{mc}(1.20Dr^{-1.44} - 0.2)$. The secondary flow parameters for the main channel and floodplain were calculated as a fraction of the bed shear stress from (Eqs. 24 & 25) with values of $k_{mc} = 0.15$ and $k_{fp} = -0.25$ as recommended by Abril and Knight (2004).

[Figure 4 can be inserted here]

[Figure 5 can be inserted here]

From Figure 4, it can be seen that for all flow cases, the analytical solutions for U_d in the main channel agree reasonably well with the experimental data. However, it seems that the simulated distributions for U_d in the floodplain region do not match closely with the measured ones, particularly for flow cases of relatively high relative depth ($Dr > 0.33$). In that region, the lateral distributions of U_d are underpredicted as clearly shown for the cases CS3 and CS4 (Figure 4c and 4d).

Similar trends for boundary shear stress (τ_b) from SKM1 application can be observed in Figure 5. There is a good agreement between the simulated results (dashed lines) and experimental data for τ_b in the main channel, but the results show that the simulated distributions of τ_b are underpredicted in the floodplain, in particular for high flow cases ($Dr > 0.33$). It should be noted that the agreement of the predicted results for U_d with the experimental data is relatively better than that for the τ_b results. This is because τ_b is related to U_d by a quadratic relationship, consequently the error in prediction of τ_b is larger.

The results obtained from SKM1 application indicates that the conventional values of $k_{fp} = -0.25$ may not be appropriate for simulating high flows over a smooth narrow floodplain. Because the volume and mass of water in the narrow floodplain is relatively smaller than that in a wide floodplain, it would be expected that the effects of the secondary circulations between the main channel and the floodplain on the primary velocity in the floodplain are higher than that in wide floodplain channels. Thus, the value of k_{fp} should be increased to account for the increased effects of secondary currents in the floodplain region.

The smooth floodplain cases (CS1 & CS4) were re-simulated, where the friction factor and the λ values were kept unchanged and the k_{fp} was only adjusted to provide the best fit to the measured depth-averaged velocity (U_d) and boundary shear (τ_b) distributions. The results for U_d and τ_b from these simulations are referred to as SKM2 and plotted as solid lines in Figures 4 & 5. It was found that only increasing the value of k_{fp} was sufficient to improve the simulated results for both U_d and τ_b over the floodplains. The analytical results for the floodplain improved appreciably when secondary flow coefficient (k_{fp}) was doubled from -0.25 to -0.50 in the conventional expression proposed by Abril and Knight (2004).

In the light of the analysis above, it can be concluded that similar to the wide floodplains, the secondary flows effects on the streamwise velocity and boundary shear stress can be estimated as a fraction of boundary shear stress in the cases of smooth narrow floodplain such as channels considered here. However, for the narrow smooth floodplains the secondary flow effects are more significant than that in the case of wide floodplains and the shear generated due to the secondary flow may be about 50% from the mean bed shear stress.

5.2 Flow Cases with Rough Narrow Floodplains

Figures 6 and 7 show the simulated results for U_d and τ_b for all rough cases (CR1~CR4), together with experimental data. In applying the model to the rough floodplain cases, the eddy viscosity coefficients and the secondary flow coefficients in the main channel and floodplain were first assumed to be as same as their conventional values that may be applied for shallow and wide floodplain channels, i.e. $\lambda_{mc} = 0.07$, $k_{mc} = 0.15$ and $k_{fp} = -0.25$. The friction factor was estimated from the modified Darcy-Weisbach equation. The simulated results obtained using the conventional values of model parameters are plotted as dashed lines and referred to as SKM1.

For SKM1 simulation, it appears that the computed velocity (U_d) in the main channel is greater than the experimental data and its gradient is steeper than the one from the experiments, particularly for low flow cases (Figure 6a and 6b). For the higher flow cases ($Dr > 0.33$), the differences between the simulated and measured profiles are relatively small. Figure 7 also shows similar trend for the simulated results for τ_b , where τ_b profiles from SKM1 predictions are fairly in good agreement with the measured data in the floodplain regions but are not over the main channels. The simulated distribution of τ_b is overpredicted in the main channel due to the overprediction of the simulated velocity (U_d). This suggest that the assumed values of the eddy viscosity for the main channel may be underestimated, leading to the simulated profiles of U_d and τ_b that are overpredicted and steeper in that region.

[Figure 6 can be inserted here]

[Figure 7 can be inserted here]

Figures 6 and 7 shows that the predicted results for both U_d and τ_b can be improved when only the eddy viscosity parameter for the main channel (λ_{mc}) is increased to about (0.09), as shown in SKM3 profiles (solid line). As a result of λ adjustment, the SKM3 distribution in comparison with SKM1 agrees better with the experimental data; in particular, at the main channel where the profile gradient matches better to that of the measured profile.

It should be noted that the results were improved without needing to modify the conventional values for secondary flow coefficients k_{mc} and k_{fp} . This indicates that the conventional calibrated values for secondary flow parameters can effectively be used for simulating rough narrow floodplain channels. As mentioned previously, the depth-averaged velocities term $[(UV)_d]$ can

be related to the depth-averaged streamwise velocity U_d (Ervine et al. 2000), so the secondary flow effect is expected to decrease when the U_d decrease because of increased roughness. This means that in the case of rough narrow floodplains, the secondary flow has a smaller contribution in energy losses compared to the lateral shear. Thus, it is suggested that the secondary flow coefficients can be estimated as their conventional values which are recommended for wide floodplain channels.

6 Conclusions

In this study, 2D depth-averaged simulations based on Shiono and Knight method (SKM) were performed to simulate flows in asymmetric compound channels with narrow floodplains. The applicability of Shiono and Knight method (SKM) to predict the primary velocity (U_d) and boundary shear stress (τ_b) was explored. For SKM modelling, a number of empirical input parameters are required, including the bed friction factor f , the dimensionless eddy viscosity coefficient λ and the secondary flow parameter Γ . The latter two require calibration or reliable estimates to produce accurate predictions.

Two different sets of experiments were conducted, one on rectangular compound channels with smooth floodplains and the other on channels with rough floodplains. Flow cases considered in the experiments were then simulated by using the SKM model. For compound channels with smooth narrow floodplains, the calibration methodology developed by Abril and Knight (2004), which is referred as a conventional method, was found to produce underpredicted values of U_d and τ_b in the floodplain regions, particularly for the cases of relative depths (Dr) larger than 0.33. However, the simulated results can be improved after the secondary flow coefficients in the floodplain (k_{fp}) are increased from -0.25 to -0.50. This demonstrates that the secondary flow effect is more significant in smooth narrow floodplains compared to wide floodplains, and the secondary flow force would be estimated to be about 0.5 of the mean bed shear force.

For compound channels with rough narrow floodplains, the conventional values of the secondary flow coefficients can be used for predicting the primary velocity and boundary shear stress in both flow regions, but the values of eddy viscosity coefficient (λ_{mc}) needs to be adjusted in order to improve the simulation results in the main channel. In general, the conventional expressions proposed to describe the effects of secondary currents and lateral shear in wide

floodplain channels cannot be used as a universal method to obtain predictors of SKM coefficients in narrow floodplain channels.

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